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14. ABSTRACT

Project Themis is an in-house program within the Liquid Engines Branch of the Air Force Research Laboratory (AFRL). It focuses on investigation of liquid oxygen (LOX)/hydrocarbon high pressure combustion devices through subscale experimentation in combustion and inert conditions, theory development, and modeling and simulation (M&S). The Themis program has two goals: to minimize component risk and to mature new technologies that can be transitioned to future engine systems. The first helps AFRL technology demonstrators reduce risk by improving the fundamental understanding of these systems. The second focuses on the future by identifying new configurations, technologies, and materials for transition into future systems. As part of a set of Themis experiments, a facility is being activated to test the effect of supercritical conditions on the mixing of fluids in a jet-in-crossflow (JICF) configuration. This research serves as risk reduction for AFRL programs. The experiment will simulate the geometry and high pressure conditions of a liquid rocket engine (LRE) component in a non-combustion environment using inert fluids. The experiment is designed to be modular and can accommodate various injection concepts. In the current experiment, radial jets of liquid nitrogen (LN2) will be introduced into a freestream flow mixture of argon and helium at supercritical pressure. These fluids will simulate dense LOX injected into a flow of low density combusted gases. The simulant fluids have been selected to achieve large density and momentum ratios. This configuration is designed to mature the understanding of the mixing process of variable density jets in a supercritical state. This paper will describe the facility configuration, modeling of the facility using Sinda-Fluint and the challenges of activating a mothballed facility. It will also describe the experimental set-up, instrumentation and test matrix for the experiment.

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Project Themis Supercritical Cold Flow Facility, Experiment Design and Modeling for the Study of Fluidic Mixing

28th AIAA Aerodynamic Measurement Technology, Ground Testing, and Flight Testing Conference

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Ray Walsh
Pat Sgarlata

Cold Flow Mixing Study

Project Themis: In-house research program in AFRL Liquid Rocket Engine Branch

Cold Flow Study: One of several major efforts of in-house program

Purpose: Elucidate the effects of high pressure and large density ratios on fluidic mixing phenomenon

Reason: RISK Air Force programs designing LREs that operate in these poorly understood regimes using M&S

Objective: Provide experimental data that does not exist in scientific community → M&S Validation

Challenge: Accessibility to data in extreme LRE environments

Approach: Simulate key aspects of thermodynamic conditions in an accessible/inert environment

M&S Validation

Experiment Motivation

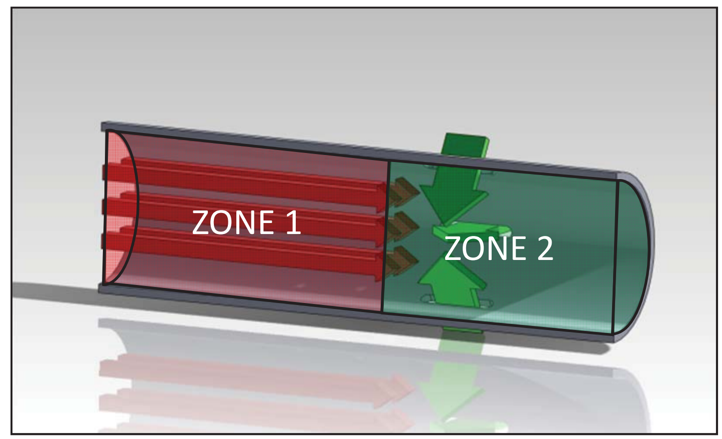
Provide Experimental Data base for Validation of M&S:

- **Supercritical fluid behavior**
- **Variable density Jets**

•Current design heavily reliant on computer M&S:

•Advantage: Single point hardware design unlike "design-build-test-fail" approach

•RISK: Current M&S tools not adequately validated in extreme LRE environment



•Mixing issues critical to LRE's

•Fluid Temperature Gradients

•Fluid Density Gradients

•Performance and material survival

•Why Fluidic Mixing?

•Intrusive mixing devices require frequent inspection

•Approach:

•Zone 1: Combustion region → Low density axial freestream flow

•Zone 2: Injection/mixing region → Secondary high density radial injection

Validation

Supercritical conditions and large density ratios are a significant departure from most JICF studies

- No previous need to investigate the effects of these conditions
- Typical studies have not explored regimes of supercritical pressures and large density ratios
- Pressure and Density: key to the veracity of M&S

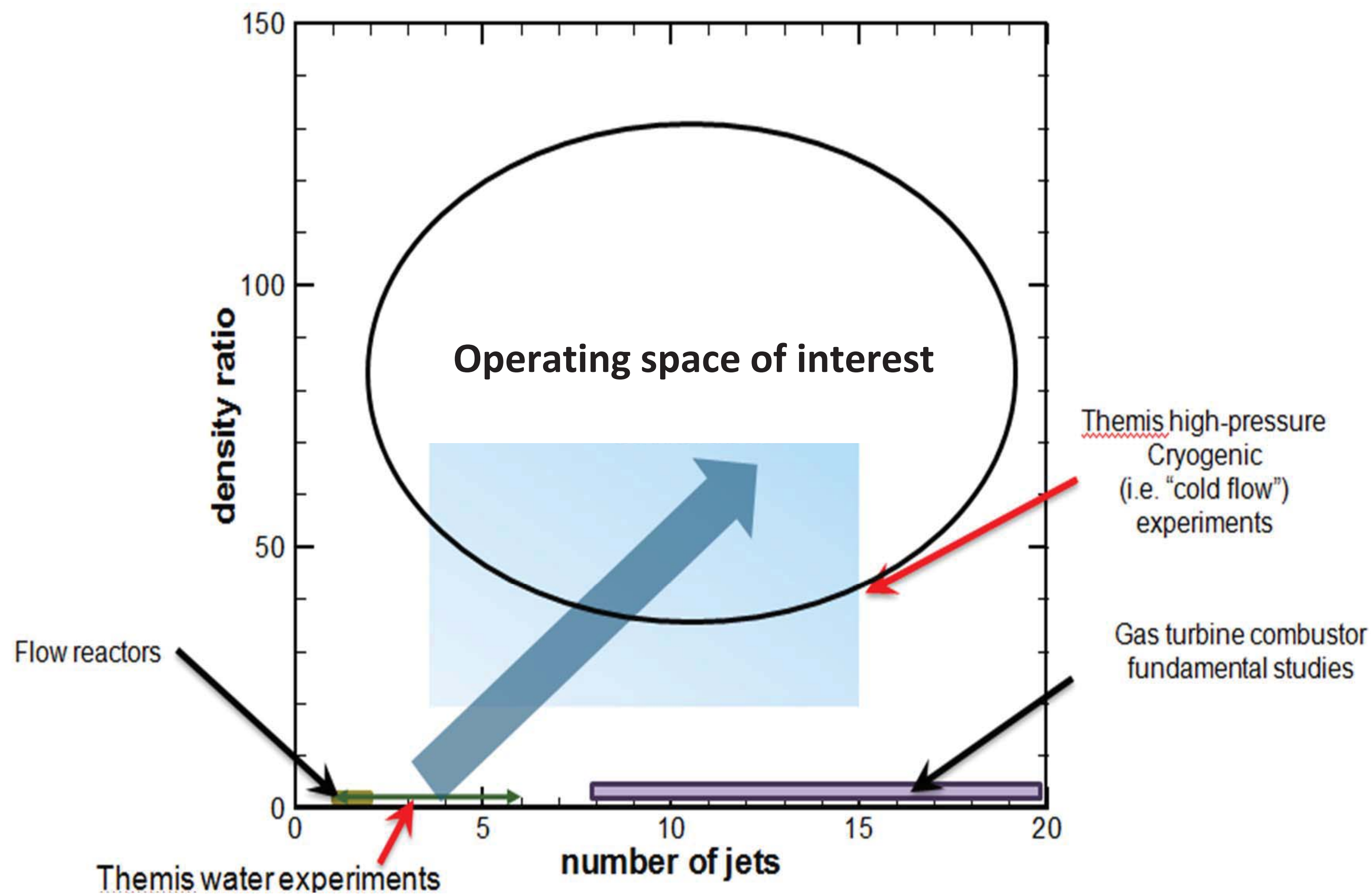
	Pressure (psia)	Temperature (R)	Density Ratio
LRE Components	>>Supercritical	>>Supercritical	<<1
Typical Gas Turbine Study	Ambient	Ambient	1

Cold flow experiment is a compromise between:

1) Realistic environment of the combustion device
2) Lab bench study

- Intrusive measurements in combustion devices limited by instrumentation survivability
- Non-intrusive techniques not sophisticated enough to extract comprehensive information
- Lab scale cannot achieve combination of Pressure and Re# on required scale

Exploring Relevant Regime



Cold Flow Experiment and Facility Constraints

Factors considered in the cold flow experiment and facility configuration:

1) Maximizing operating pressure
2) Operating at supercritical conditions
3) Capability of wide ranges of jet-to-gas density and momentum ratios
4) Adoption of preferably safe, non-toxic fluids
5) Repeatable and reproducible flow conditions at low cost
6) Availability and cost of simulant fluids
7) Cold flow hardware to allows configuration change and accommodates diagnostics

Initial Cold Flow Simulant Fluid Candidates

Simulant Fluids	Pressure	Phase	Jet Temp	Freestream Temp	Jet Density	Freestream Density	Density Ratio
Jet/Freestream	(psia)	Jet/Freestream	(°R)	(°R)	(lb/ft^3)	(lb/ft^3)	Jet/Freestream
CO_2/N_2	1000	liquid/supercritical	535	535	47.1	4.89	9.6
CO_2/N_2	1000	liquid/supercritical	400	1480	73.2	1.72	42.6
CO_2/CH_4	1000	liquid/supercritical	535	535	47.1	3.15	15.0
CO_2/CH_4	1000	liquid/supercritical	400	830	73.2	1.81	40.4
RP-1/N_2	1000	liquid/supercritical	535	535	50.4	4.89	10.3
RP-1/N_2	1000	liquid/supercritical	535	2030	47.1	1.26	37.4
R12/N_2	1000	liquid/supercritical	535	535	84.2	4.89	17.2
R12/N_2	1000	liquid/supercritical	535	1210	84.2	2.10	40.2
CO_2/He	1000	liquid/supercritical	535	535	47.1	0.68	69.7
N_2/He	1000	supercritical/supercritical	248	535	27.1	0.68	40.1

Simulant Fluid Selection

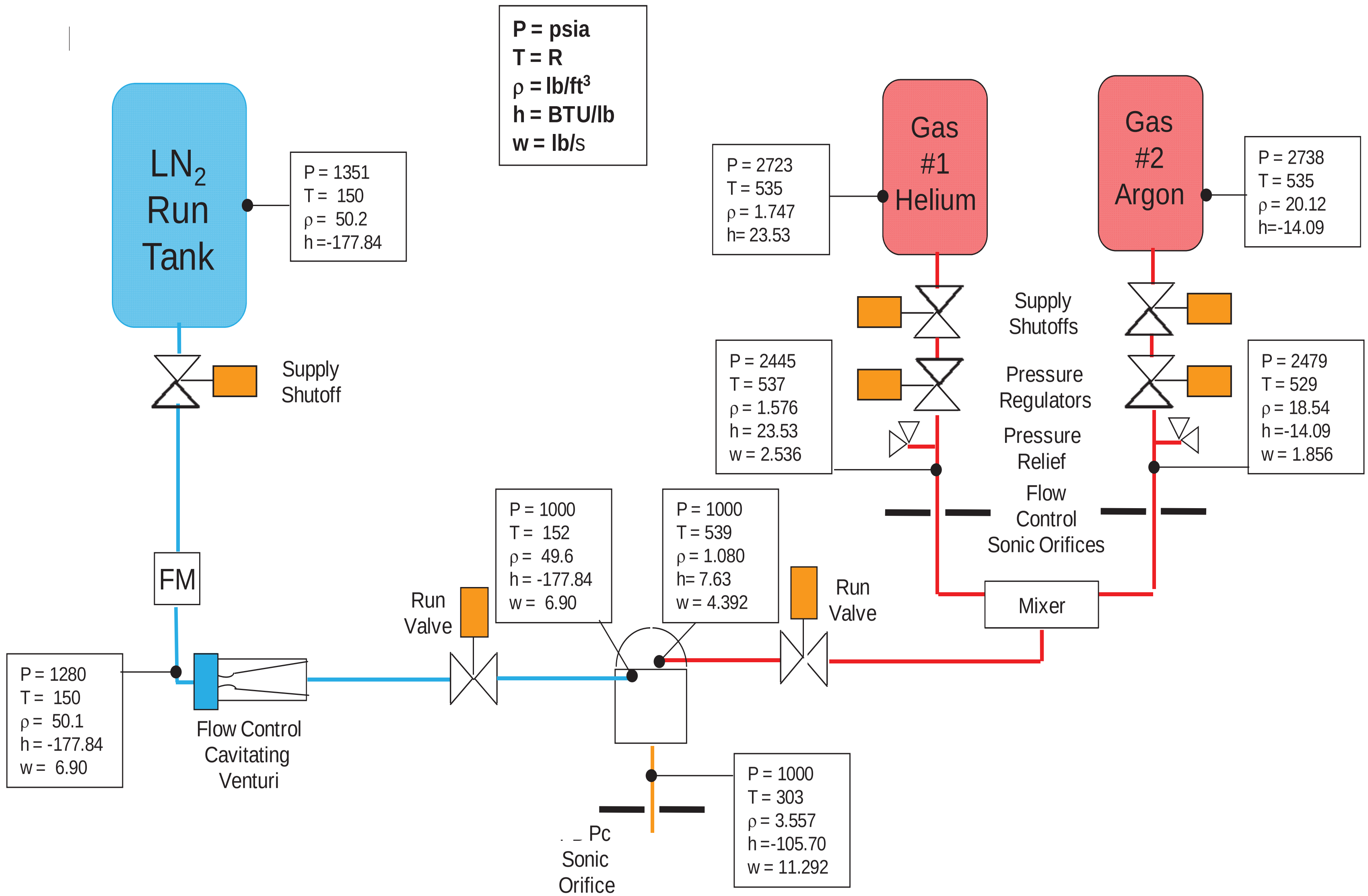
- **Sample density ratios from the candidate fluid list were generated**
  - using nitrogen as diluent species and helium as freestream species could achieve a wide range of density ratios
  - Both nitrogen and helium satisfy safety, toxicity, and availability concerns
- **Chilled nitrogen gas can achieve desired density ratio range**
- **Issues of using chilled nitrogen gas**
  - Filling a vessel with cold nitrogen gas at prescribed and repeatable conditions complicates operations
  - Variation of the nitrogen properties during expulsion presents flow control and experimental difficulties;
  - For high density ratio case, the nitrogen is close to the critical point possibly resulting in two phase flow during expulsion
- **Solution to problem is use of liquid nitrogen versus cold gas**
  - Storage, flow control, and phase control of LN_2 is straightforward
  - only density ratio that can be achieved is ~74 which is well above the range of interest.
- **Second approach: mix helium with a second high molecular weight gas**
  - yielding freestream gas density variations which could tolerate liquid nitrogen as the diluent
  - Two safe and inert candidate gases were identified: neon and argon
- **Argon was selected because cost of neon is prohibitive**

	Helium/Neon Mixture	Helium/Argon Mixture
	Cold Flow P =1000 psia	Cold Flow P =1000 psia
Freestream Species	**Helium/Neon**	**Helium/Argon**
Temperature, R	535	535
Helium/Second Gas Tcrit, R	9/80	9/271
Helium/Second Gas Pcrit, psia	33/395	33/705
State	supercritical	supercritical
Pure Helium/Second Gas Density, lb/ft3	0.676/3.40	0.676/7.22
Jet Species	**Liquid Nitrogen**	**Liquid Nitrogen**
Temperature, R	150	150
Tcrit, R	227	227
Pcrit, psia	493	493
State	supercritical	supercritical
Density, lb/ft3	49.80	49.80
Initial Density Ratio, ρ_{jet}/ρ_{gas}		
Minimum (pure Second gas)	14.6	6.9
Maximum (pure Helium)	73.7	73.7

Density ratio ranges for helium/neon and helium/argon mixtures

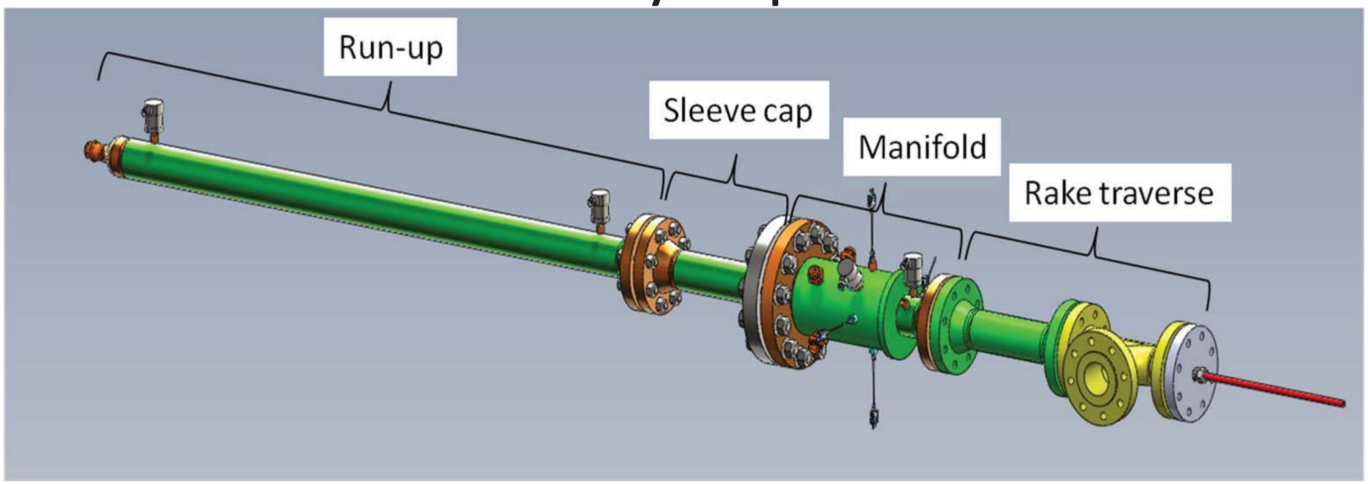
Fluid selection was a balance between requirements and cost

Initial Cold Flow Schematic

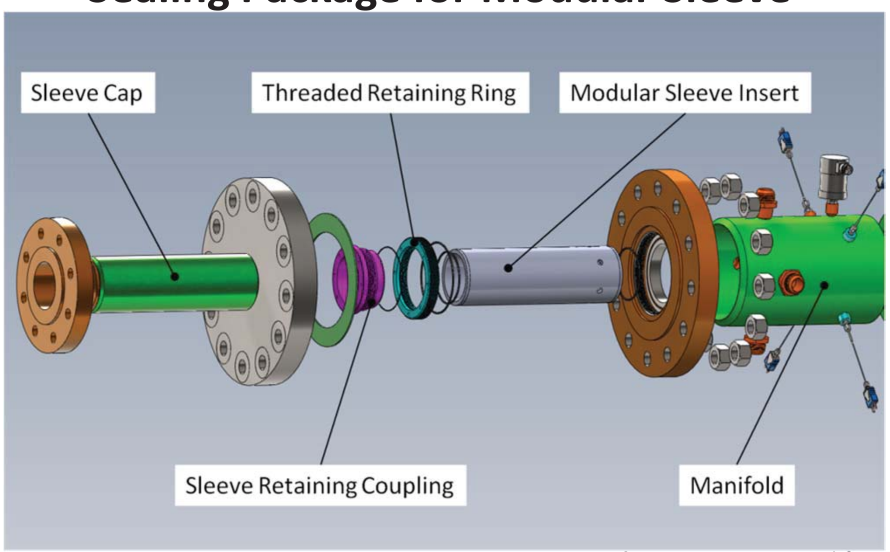


Test Article

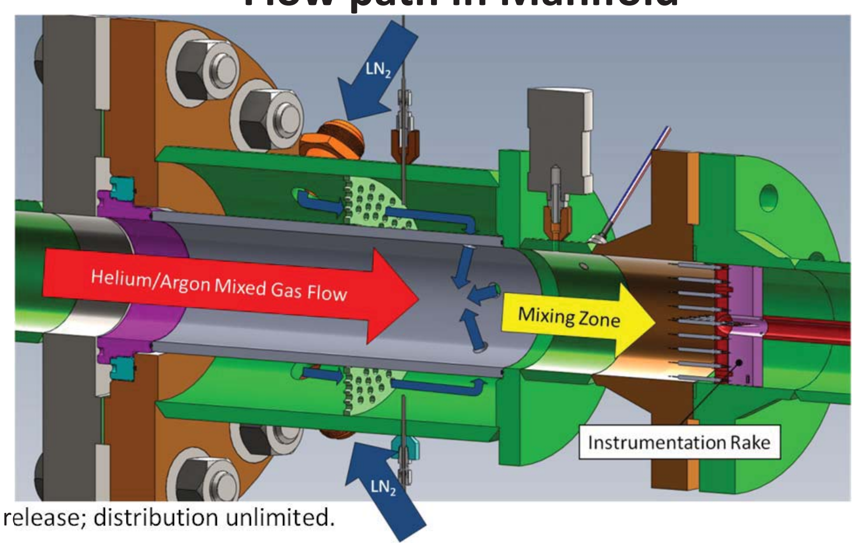
Test Article Assembly Comprised of 4 sections:



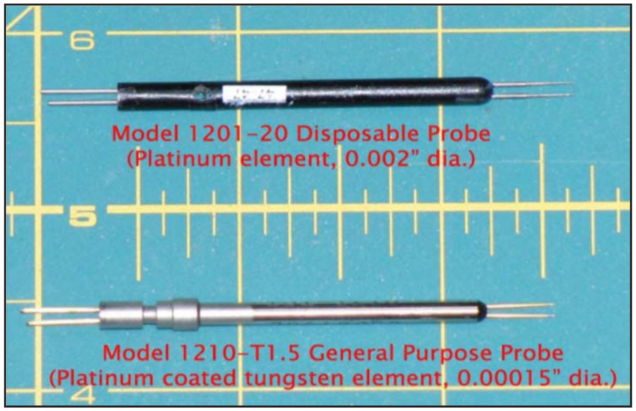
Sealing Package for Modular Sleeve

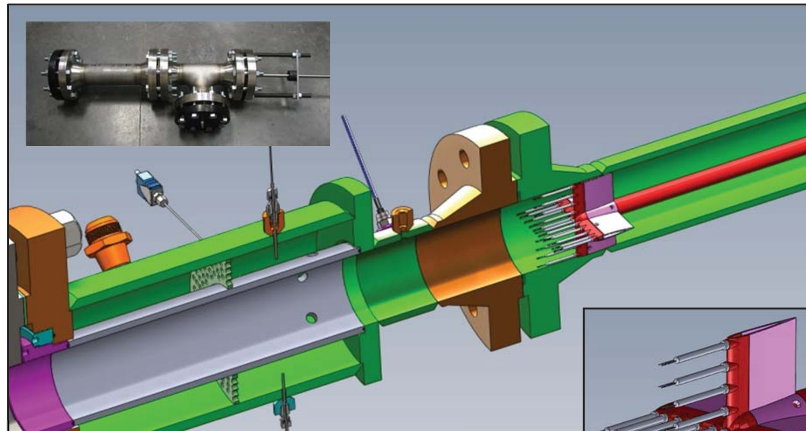


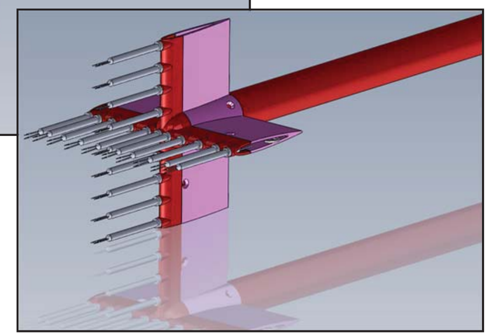
Flow path in Manifold

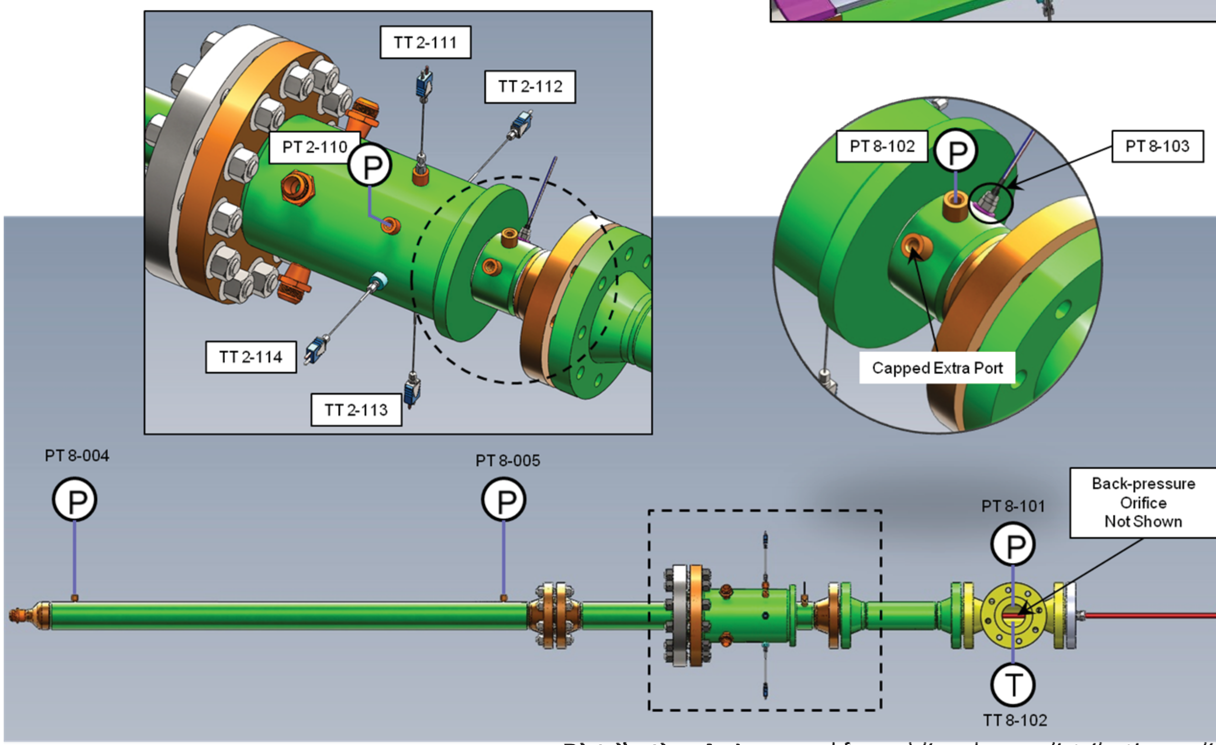


Test Article Instrumentation







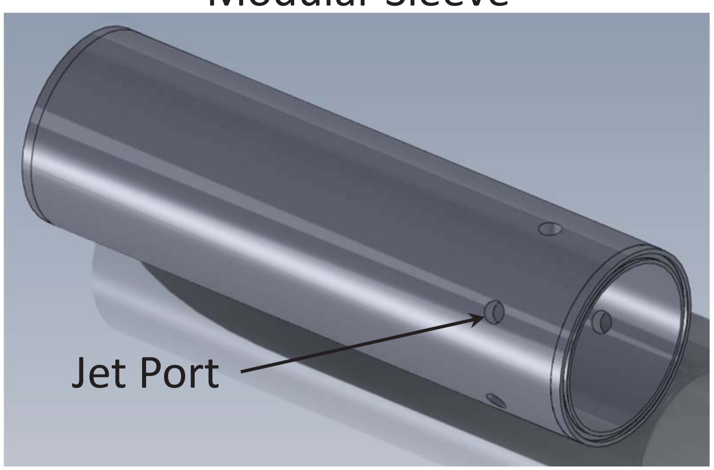


Test Matrix

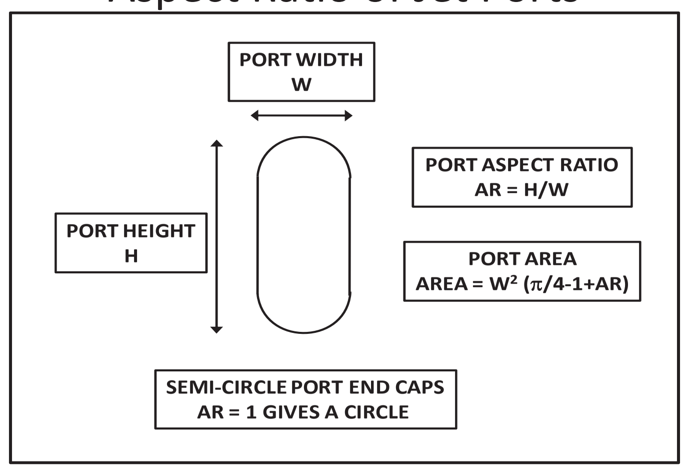
{Port Geometry} - {# of Ports} – {Aspect Ratio} – {Momentum Flux} – {Run Number}

Test ID	Subtest	Run	# of Injection Ports	Momentum Flux Ratio (J)	Aspect Ratio	Diameter (in)	Argon/Helium Pressure (PSIA) & Temp (R)	LN_2 Pressure (PSIA) & Temp (R)
C-4-1-10-1	1	1	4	10	1	0.519	1,000/530	1,000/150
C-4-1-10-2	1	2	4	10	1	0.519	1,000/530	1,000/150
C-4-1-20-1	2	1	4	20	1	0.436	1,000/530	1,000/150
C-4-1-20-2	2	2	4	20	1	0.436	1,000/530	1,000/150
C-4-1-30-1	3	1	4	30	1	0.394	1,000/530	1,000/150
C-4-1-30-2	3	2	4	30	1	0.394	1,000/530	1,000/150

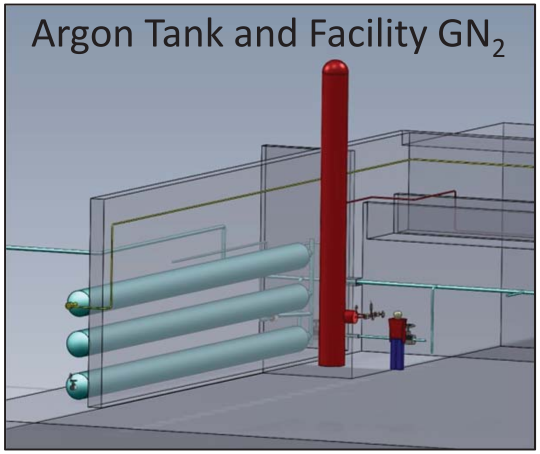
Modular Sleeve



Aspect Ratio of Jet Ports

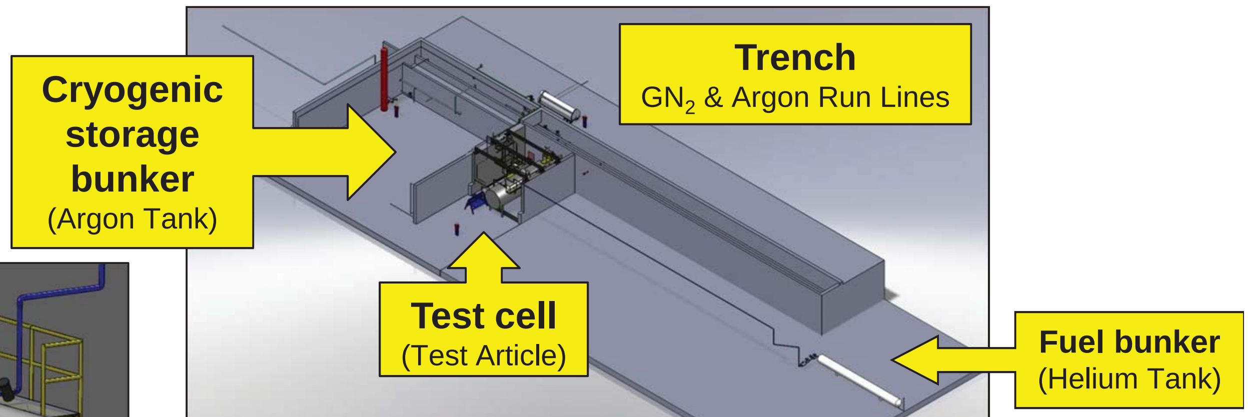


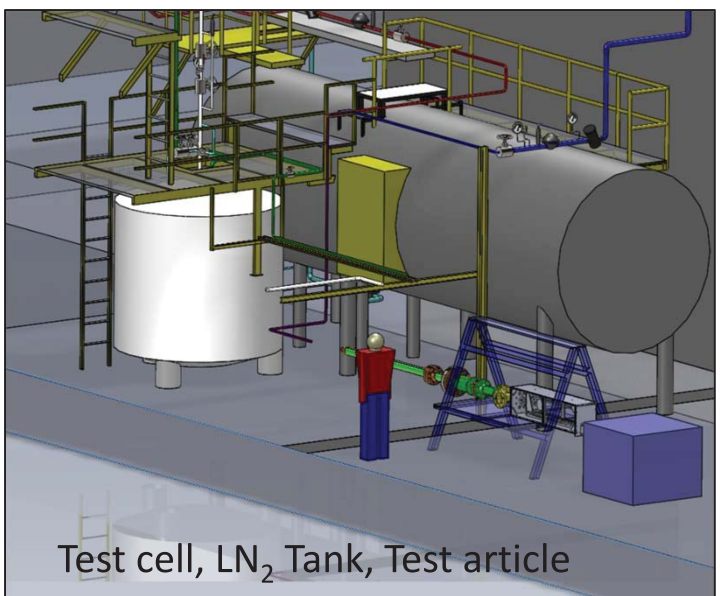
Facility

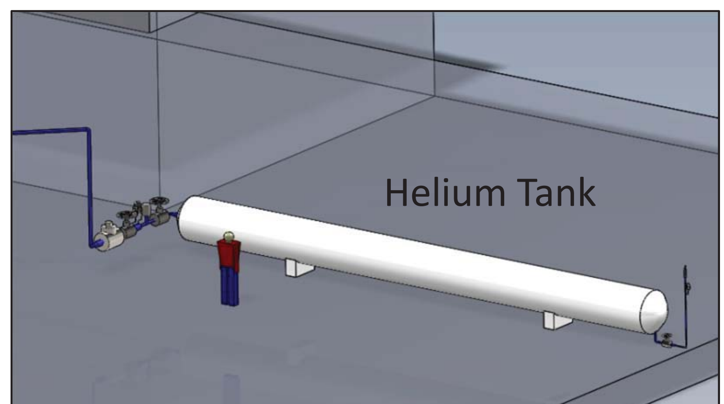


AFRL Test Area Selection Criteria:

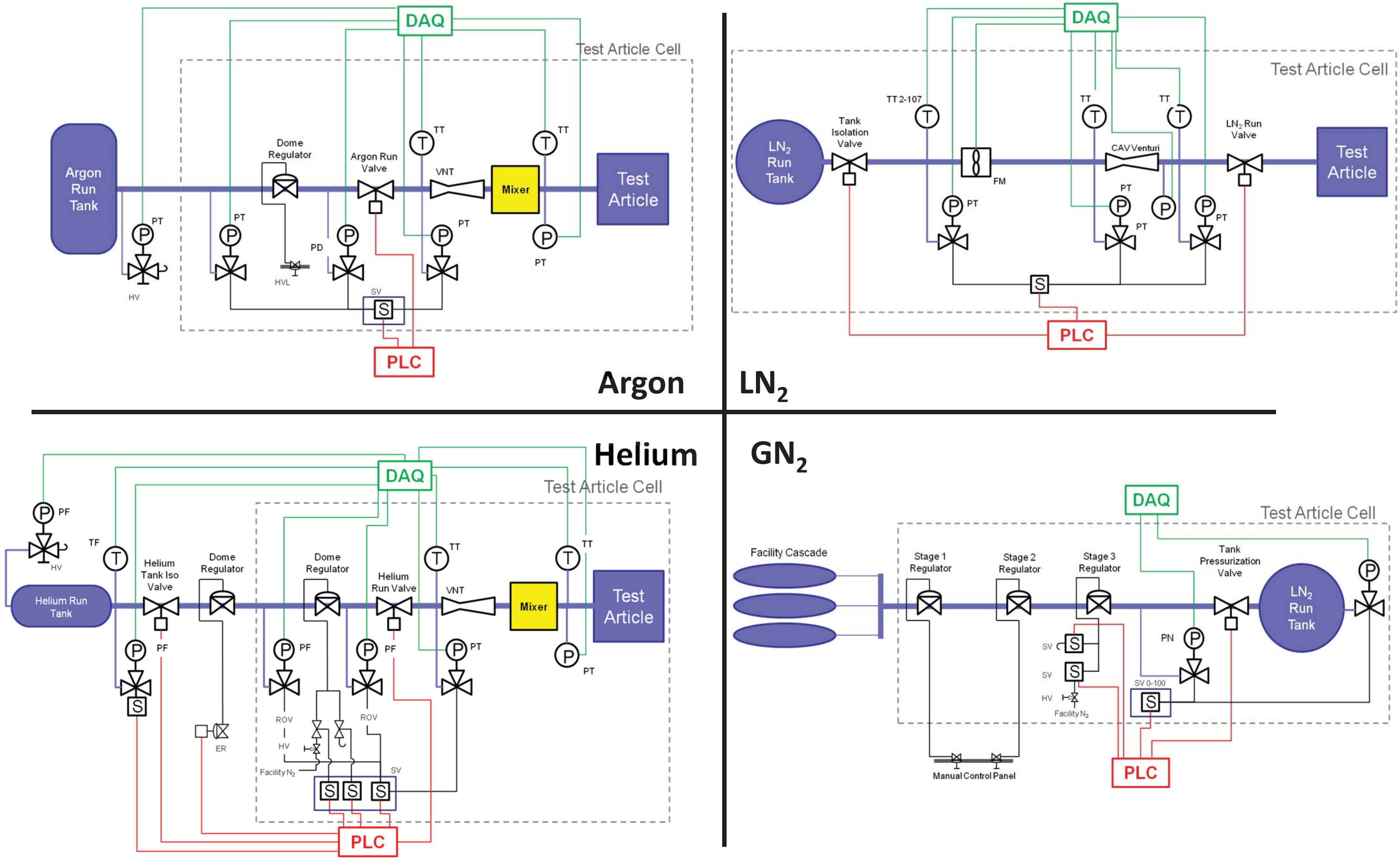
1) High pressure/high volume tankage
2) High pressure/large diameter piping
3) Existing flow control components
4) Remote facility control (PLC)
5) High pressure GN2 supply
6) High speed DAQ





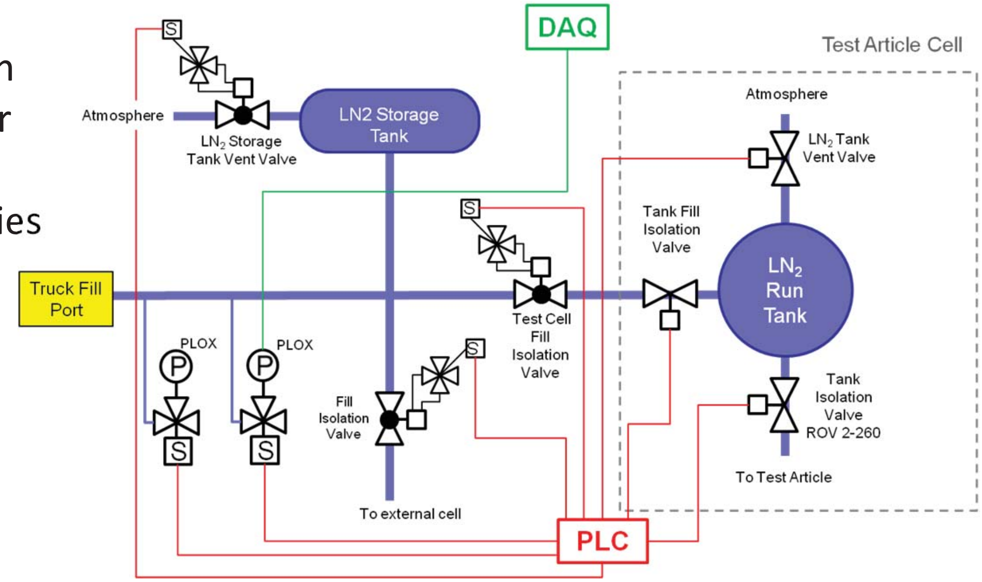


Facility Fluid Networks



Support Hardware

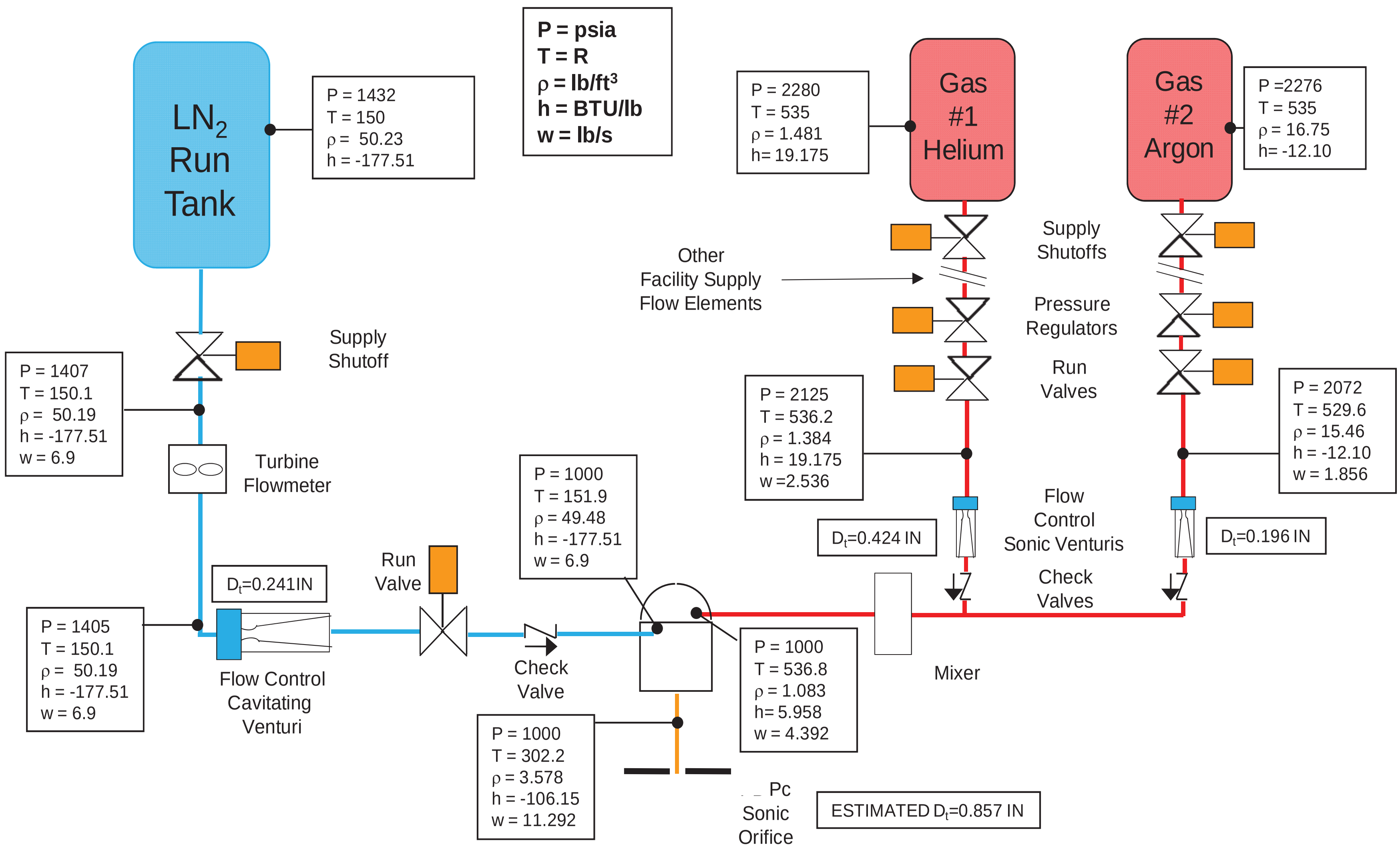
- Liquid nitrogen stored in low pressure vacuum jacketed storage tank located in the LOX bunker
- Originally used to store LOX
- Used to replenish the LN_2 run tank as test series dictates.
- Components are rated to handle colder temperatures of LN_2



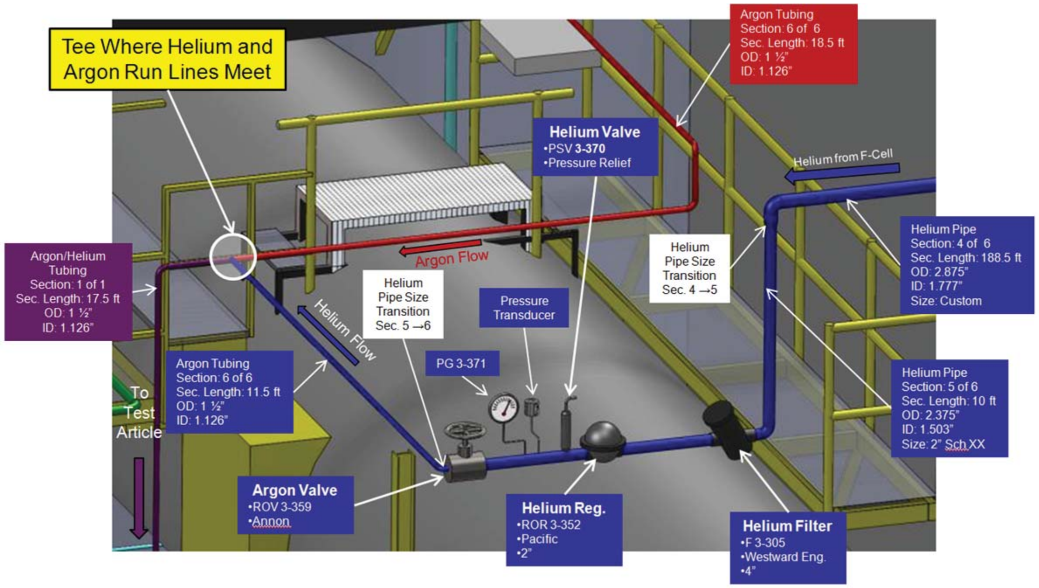
Gas booster system for charging Argon and Helium Tanks

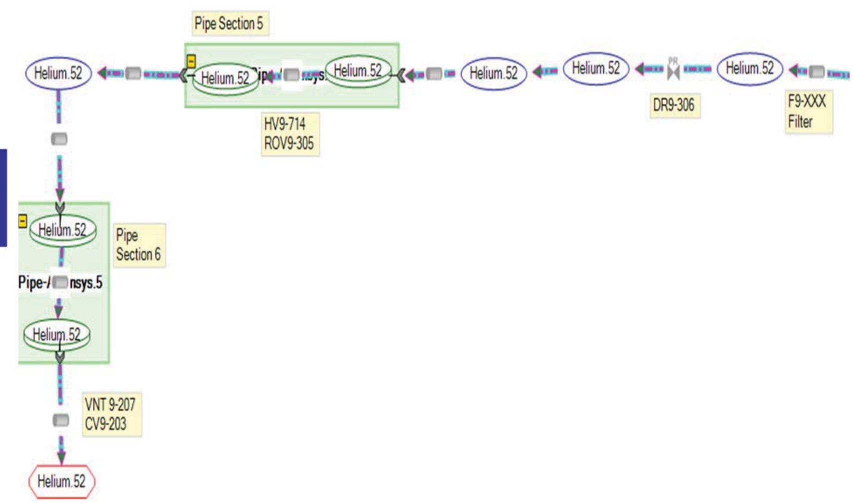
- Recover residual bank trailer fluids
- Charge up to 6000 psi
- Short transfer times
- Dry air seal package

Design and Off-Design Baseline Analysis

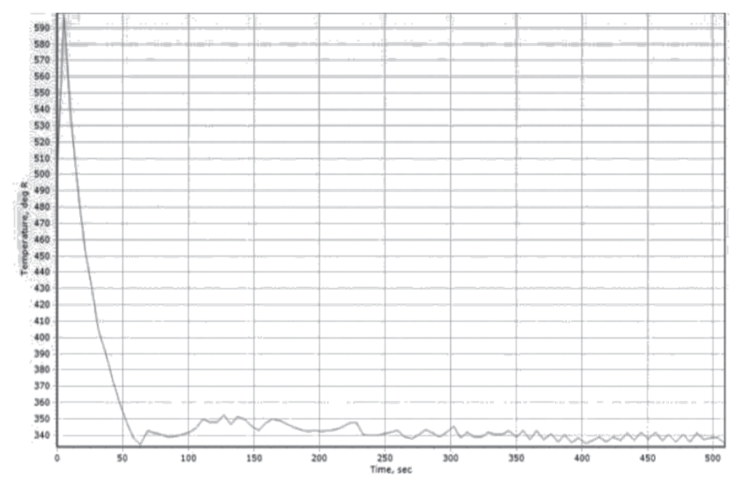


Sinda/Fluint Analysis





- Model consists of three separate fluid sub-models for the LN_2, helium and argon systems
  - Models are carried from the storage tank to the mixer
- The objectives of the model are as follows:
  - Simulate the steady state operating conditions of the mixing experiment
  - Estimate the Cv's of valves
  - Perform transient modeling
  - Assess issues with pressurization of GN_2 over LN_2
- During shakedown tests the model can be used to help estimate the target values to reset regulators
  - This should minimize the number of shakedown runs that are necessary.



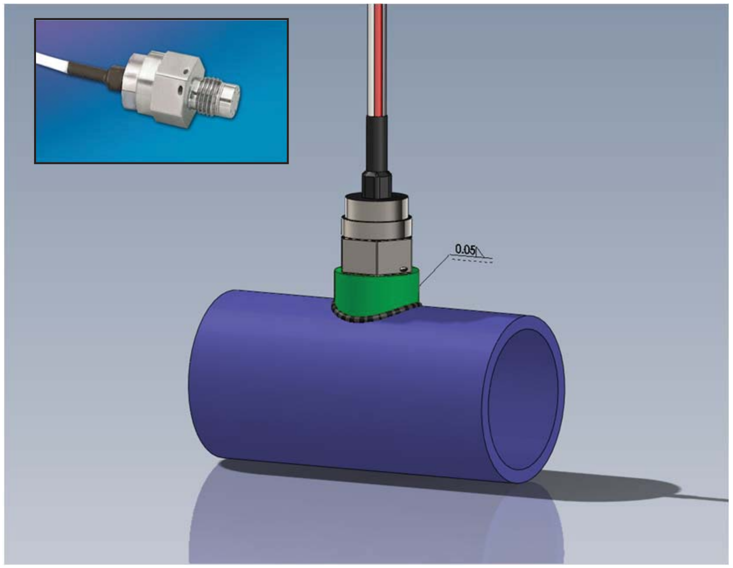
Sinda/Fluint model LN_2 run tank ullage temperature predictions

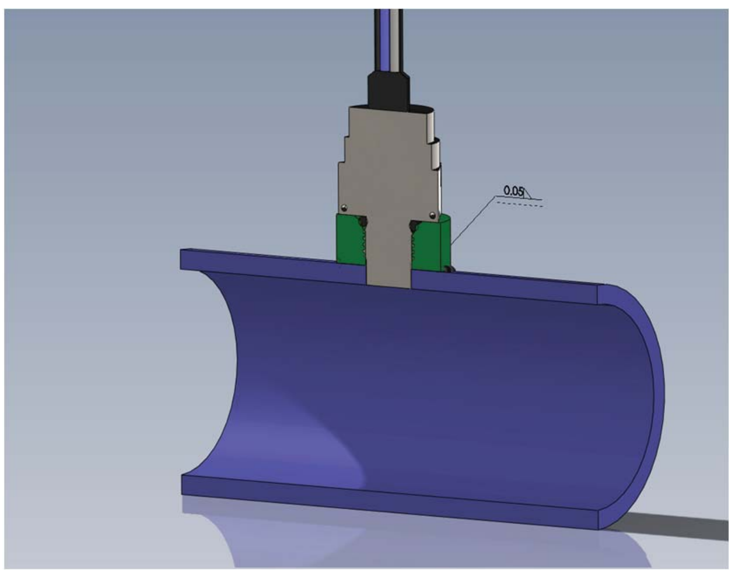
Summary

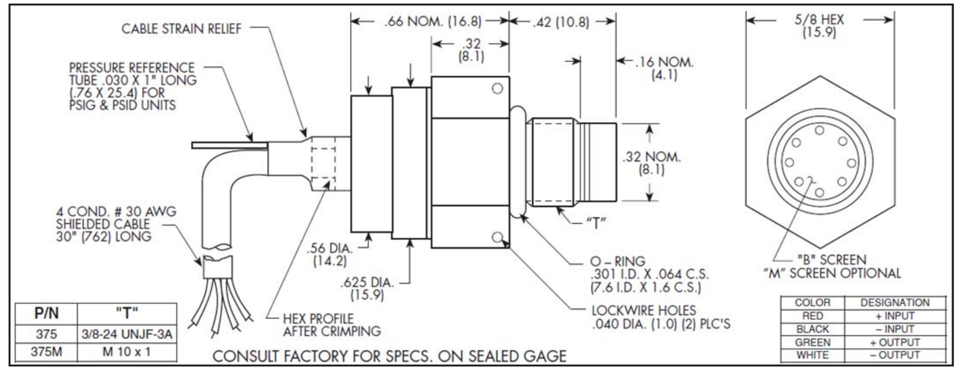
- Project Themis cold flow mixing study scheduled to begin late Summer 2012
- Current efforts:
    - Revamping of outdated control room software
    - Calibration of facility pressure transducers
    - Installation of the test article
    - Back pressure orifice fabrication
- Test capability provide ongoing means to extract experimental data from high pressure regimes
- Allow greater understanding of the physical mechanisms that govern the complex interactions associated with fluidic mixing
- Data will fill a void in scientific community database with respect to the effects of supercritical conditions and density disparities on fluid flows
- Data to be used to validate M&S programs used to design hardware that operates in these regimes

Back-up Slides

Kulite Wall Mount







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BLACK	– INPUT
GREEN	+ OUTPUT
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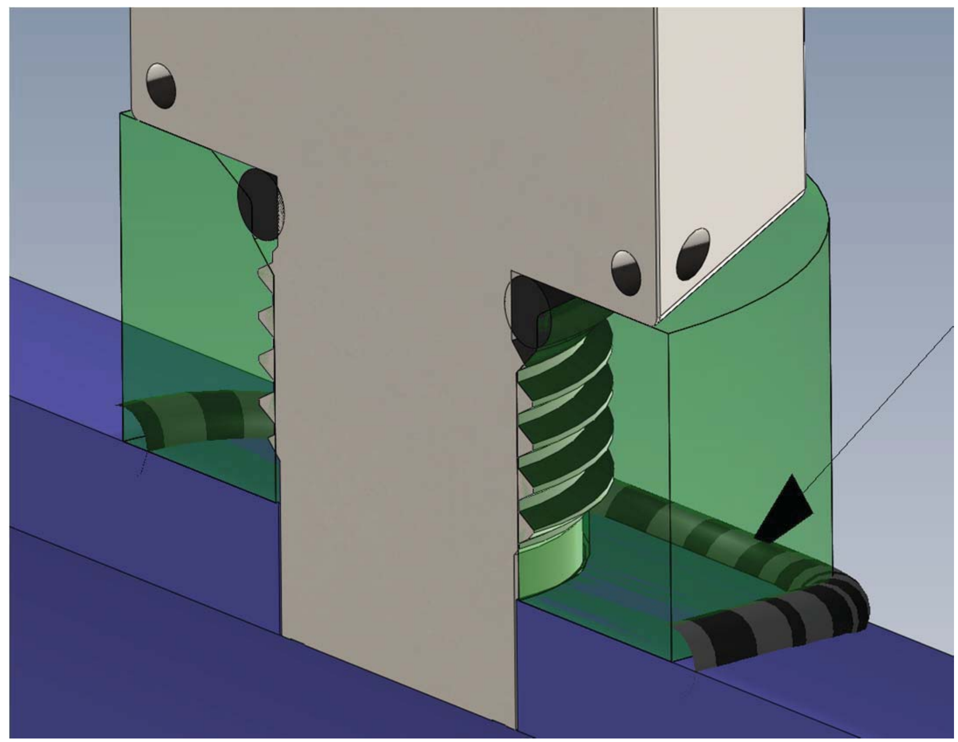
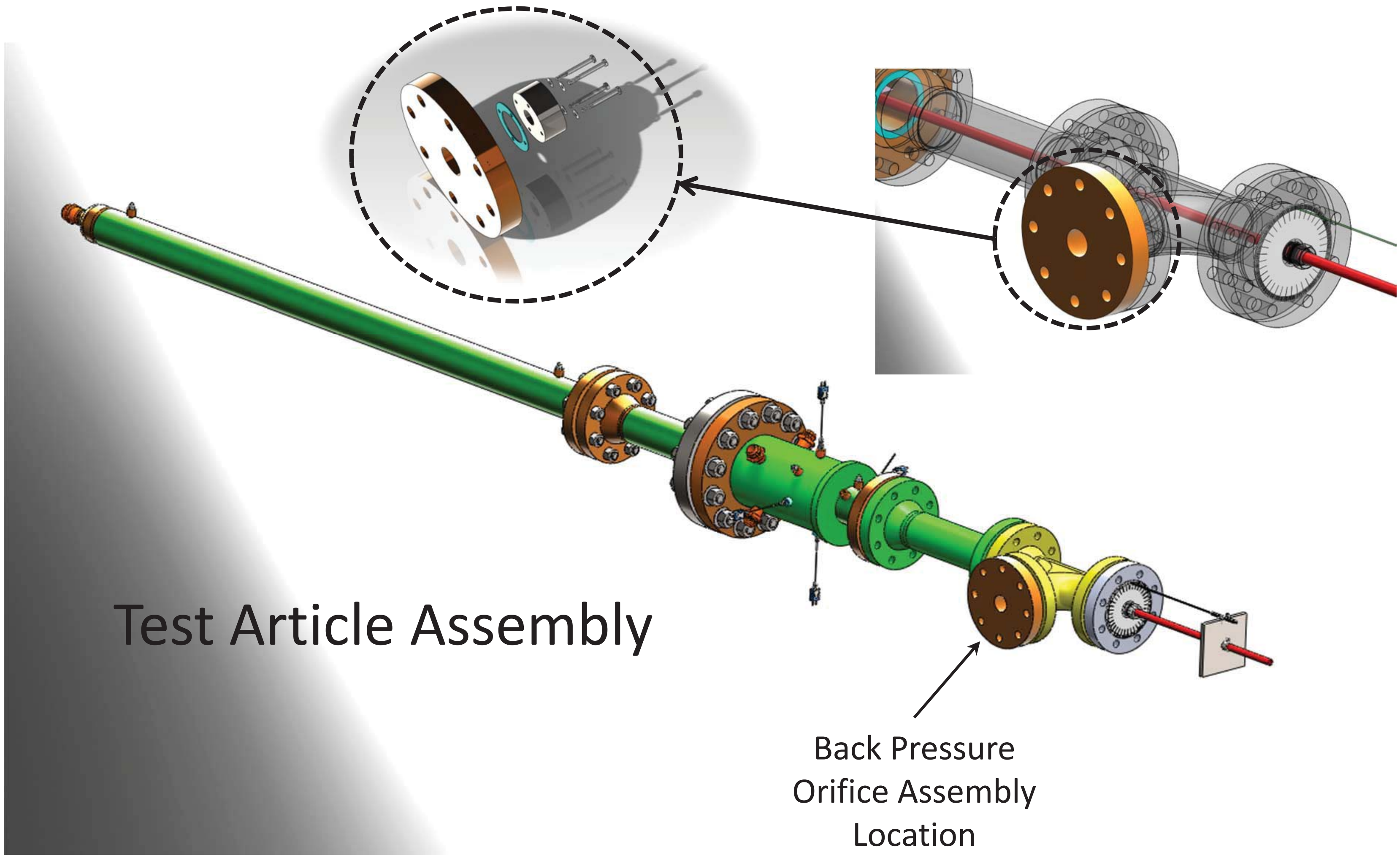


Back Pressure Orifice Assembly



Back Pressure Orifice Assembly

- Expected Discharge Coefficient: **0.598**
- From ISO-5167: Cd(Re#, D)
- D = 1.08”
- Sensitivity: 100 psi per 0.050”
- Thrust: 859 lbf